Urban Stormwater Management: Comparative Analysis of Traditional and Sustainable Approaches for Ecological Restoration

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Abstract. With the intensification of global urbanization and climate change, the natural hydrological cycle has been significantly disrupted, resulting in increased frequency of flooding, increased pollution from non-point sources, and degradation of ecosystems. This study systematically reviews traditional and sustainable stormwater management methods, focusing on their technical characteristics and application effects in urban ecological restoration. Through case studies, the paper discusses the application results of low impact development (LID), sponge city and intelligent stormwater management system. For example, in the Sponge City pilot in Suzhou, the nitrogen and phosphorus reduction rates in stormwater wetlands reached 62% and 46%, respectively, while the vegetation-filtered zones significantly increased biodiversity. This study found that, compared to traditional centralized management methods with rapid drainage as the goal, the sustainable approach not only significantly improves water quality, but also enhances the climate resilience of cities through ecological restoration and resource optimization. The significance of this study is to integrate nature-based solutions with advanced technologies, providing theoretical support and practical guidance for urban water management and ecological restoration. It offers innovative pathways to tackle climate challenges and directs future interdisciplinary stormwater management research and practices.

Keywords: Sustainable Stormwater Management, Low Impact Development (LID), Sponge City, Urban Ecological Restoration.

1. Introduction

In recent years, the rapid development of global urbanization has significantly changed the pattern of natural hydrological cycle, especially in high-density urban areas, where the impermeability of land has been greatly reduced, resulting in a series of complex environmental and social problems. These include increased frequency of flooding, dramatic increases in non-point source pollution loads, and consequent degradation of ecosystems [1]. Studies have shown that for every 1% increase in land impermeability, surface runoff can rise by up to 40% while permeability decreases by more than 50 [2]. More importantly, the additive effects of climate change have further increased the intensity and frequency of extreme rainfall events, a trend that has been validated in observational and modelling studies across multiple regions [3].

Under the framework of Sustainable Development Goals (SDGs), how to effectively deal with the challenges of water resources management caused by urbanization has become a core issue of global concern. SDG 11 explicitly calls for "inclusive, safe, resilient and sustainable cities," which require integrated management of stormwater runoff and ecological restoration mechanisms [4]. At present, the traditional single-target drainage system has been unable to meet the increasingly complex urban water resources management needs, and its technical bottlenecks are mainly reflected in the lack of non-point source pollution reduction capacity and poor adaptability to flood events [5]. Therefore, the development of innovative stormwater management methods and the systematic assessment of ecological effects have important theoretical and practical significance for promoting urban sustainable development.

Based on the above background, this study will systematically review traditional and sustainable stormwater management methods, focusing on their technical characteristics and application effects in urban ecosystems. In addition, this paper will explore the specific mechanisms and key effects of stormwater management technology in ecological restoration and propose future research directions [6]. Through the cross-integration of multidisciplinary research, this paper aims to provide theoretical basis and technical reference for the collaborative optimization of urban water resources management and ecological restoration.

2. Review of urban stormwater management methods

2.1. Traditional rainwater management methods

Traditional methods play a central role in urban stormwater management, reducing the risk of stagnant water through rapid drainage and rainwater collection, ensuring urban safety and water resource utilization, but they are still inadequate in addressing ecological sustainability and pollution control.

2.1.1. Centralized drainage system

Centralized drainage systems are at the heart of traditional urban stormwater management approaches, using underground drainage networks to rapidly discharge stormwater to reduce surface accumulation and flood risk [1]. The main advantage of this method is that it is designed to efficiently channel rainwater and quickly mitigate the effects of urban waterlogging. However, the impact of this system on the downstream ecosystem is gradually emerging, such as the rapid transfer and accumulation of pollutants may lead to the deterioration of the river ecological environment [2]. In addition, the mixed discharge of stormwater and sewage increases pollution transfer and limits the feasibility of water quality control [7]. Academic studies have pointed out that traditional drainage systems often ignore water quality management objectives and do not meet modern ecological sustainability requirements. This suggests the need to add water quality control functions in addition to centralized drainage to achieve a balance between ecological and water resources management objectives [8].

2.1.2. Rainwater collection and storage technology

Rainwater collection and storage technology, as a traditional management method, realizes the effective use and management of rainwater resources through the installation of small storage tanks and underground reservoirs in cities [9]. The core functions of this technology include reducing surface runoff and providing a stable source of water for non-potable uses such as irrigation or industrial water [10]. For example, in places such as Japan and Australia, rainwater harvesting systems have been widely used and have significantly improved water efficiency by combining with green space systems, in Australia, rainwater harvesting systems, with more than 70% penetration, reduce about 200,000 cubic metres of urban runoff per year into waterways, significantly improving water efficiency and reducing urban drainage pressure [11]. However, these technologies also face high maintenance costs and limitations due to substandard rainwater quality. Recent research has shown that the capacity of stormwater harvesting systems during heavy rainfall events can be effectively increased by introducing automated discharge technologies or tiered storage designs, while reducing adverse impacts on water quality [12].

2.1.3. Comprehensive evaluation of traditional Methods

While traditional stormwater management methods have played an important role in mitigating urban flooding and securing water supplies, their limitations are emerging, particularly in terms of non-point source pollution reduction and ecological restoration [9]. Therefore, in modern urban stormwater management, it is necessary to further integrate traditional methods with sustainable management technologies, such as low impact development (LID) and intelligent stormwater management system, in order to make up for the defects of traditional methods and provide support for ecological protection and efficient use of water resources [10].

2.2. Sustainable stormwater management methods

2.2.1. LID

LID is the practice of minimizing stormwater runoff through distributed management and naturalization measures. One of the main goals of LID is to replicate the natural hydrological cycle. Therefore, rainwater source control is an attempt to encourage LID practice. It insists that instead of transporting rainwater, more attention should be paid to how to make better use of stormwater resources and reduce their harm to ecosystems through technology.

Rain gardens are a core component of LID. It filters through plants and soil to absorb contaminants carried by rainwater; its function is to seep rainwater into the ground. This reduces non-point source pollution; it also creates greener Spaces and habitats within the city. One study demonstrated that rain gardens have specific requirements for plant species and soil structure, depending on local conditions, for optimal purification and stormwater management functions [8]. The purification effectiveness of rain gardens depends on the plant species and soil characteristics, so the design needs to be optimized for local climate conditions and pollution source types. For example, in areas with high rainfall and complex pollution sources, it is recommended to choose plants that are resistant to flooding and can absorb heavy metal pollution, while combining soil with high permeability and organic matter to maximize purification capacity and ecological benefits [8, 10, and 13]. This adaptive design improves the long-term operational efficiency of rain gardens and ensures that they perform optimally under different environmental conditions [11].

Permeable paving is an option to reduce surface runoff through highly permeable materials. Paving materials not only allow rainwater to sink into the ground quickly, but also reduce the risk of flooding and reduce the recycling of non-point source pollution loads. More recently, recycled materials have been developed into permeable pavements. They not only improve penetration efficiency, but also reduce resource consumption [14]. Although permeable pavement can reduce runoff, its construction and maintenance costs are high, it is easy to block by pollutants and needs to be cleaned regularly, and its frost resistance in cold areas is poor, affecting its durability. Therefore, the design should be optimized according to climate conditions and pollution sources [14-16].

Green roofs are an integral part of LID technology. It absorbs and stores rainwater directly by planting plants on the roof, thereby reducing surface runoff. Studies have shown that green roofs work best in areas that can effectively capture rainfall, significantly reducing peak runoff and urban heat island effects [17].

In general, LID technology can effectively reduce urban rainwater runoff through diversified means, improve ecosystem functions, and improve the utilization efficiency of rainwater resources [18].

2.2.2. Sponge City concept

Sponge city is a systematic rainwater management method based on LID theory. Its main goal is to optimize water resource management and ecological protection by absorbing, storing, permeating and purifying rainwater. Compared with a traditional stormwater management measure, the traditional method aims rapid drainage and mainly relies on centralized drainage systems and hard infrastructure. Although it can effectively reduce surface water, it is easy to pollute downstream ecosystems and neglect the recycling of water resources [15, 12]. Sponge cities emphasize natural stormwater cycling through LID technologies and green infrastructure to absorb, store and purify stormwater, reduce runoff and improve water quality [14, 16]. In addition, the sponge city incorporates the urban heat island effect, ecological protection and landscaping into the design goals, and pays more attention to the synergy with natural systems, reflecting the new integrated water resources management concept [16,17]. This shift from "end management" to "source control" has greatly improved the ecological sustainability and versatility of urban stormwater management [9].

One of the key technologies of rainwater wetland sponge city includes rainwater wetland, where nutrients such as nitrogen and phosphorus in water will be filtered and degraded by plants and microorganisms to reduce the eutrophication and pollution of natural water bodies. In addition, it can improve urban green space coverage and promote biodiversity. [15].

The second stormwater storage tank is an efficient water storage facility capable of storing excess rainwater during heavy rains and for non-potable uses such as irrigation or industrial water in times of drought. It can regulate the timing of rainwater flow into the natural environment to enhance the effectiveness of stormwater management [16].

The third vegetation filter zone is another important measure. By combining green space and landscape design, these ribbon facilities can trap and purify suspended particles and pollutants from stormwater runoff, while adding green elements to the city. Studies have shown that vegetation filtration belt can effectively improve urban environmental quality [13] while reducing the pollution load of stormwater runoff.

In sponge city pilots in Wuhan and Xiamen, stormwater wetlands, cisterns and vegetation filtration zones significantly reduced the risk of waterlogging and runoff pollution. In Wuhan, the frequency of waterlogging was reduced by more than 30%, and the runoff reduction rate reached 50%-70%. Xiamen rainwater recycling rate increased to 15%, non-point source pollution load decreased by 40%-60% [18]. These results verify the actual effect of sponge city and provide reference for other cities.

2.2.3. Intelligent rainwater management system

The intelligent rainwater management system realizes real-time monitoring and dynamic regulation of rainwater management through the Internet of Things and big data technology. Such systems play a key role in urban stormwater management, collecting real-time data through sensors, including rainfall intensity, runoff and water quality indicators, and combining data analysis for precise regulation [16].

In practical applications, the intelligent system significantly reduces the risk of flooding and optimizes the efficiency of water use by dynamically regulating the operation of stormwater storage ponds. For example, in one case, an intelligent control system reduced the peak runoff during a rainstorm while extending the retention time of rainwater, thereby reducing the pressure on downstream ecosystems [19].

Combined with the weather forecasting system, the intelligent stormwater management system can deploy resources in advance by predicting the rainfall trend in real time, optimize the operational efficiency of stormwater management facilities, and further improve the overall efficiency of urban stormwater management [20].

3. Ecological restoration effect of stormwater management

3.1. Water quality improvement and pollution reduction

Stormwater management practices have demonstrated significant ecological benefits in terms of water quality improvement and pollutant reduction. Rainwater wetlands effectively remove suspended particles, nitrogen and phosphorus from runoff through filtration, adsorption and biodegradation. For example, in the "Sponge City" project in Suzhou, a stormwater wetland reduced nitrogen by 62% and phosphorus by 46% [16]. Similarly, low impact development (LID) techniques, such as rain gardens and permeable paving, have achieved a removal efficiency of 70%-85% for heavy metals and suspended solids respectively [21]. In terms of reducing the non-point source pollution load, the reduction of nitrogen can effectively alleviate the problem of water eutrophication, thereby inhibiting the excessive growth of algae and improving water transparency and ecological health [16]. The reduction of phosphorus not only reduces the growth of algae and harmful plankton, but also promotes the restoration of natural biodiversity in bodies of water such as lakes and rivers.

In addition, rainwater storage ponds are particularly good at dealing with extreme rainfall. Studies have shown that such facilities can reduce runoff by 91 percent and suspended solids by 56 percent, meeting planning targets [16]. Through the collaborative application of these technologies, stormwater management measures have greatly improved the ecological health level of downstream water bodies.

3.2. Habitat restoration and biodiversity enhancement

Stormwater management facilities not only improve water quality, but also contribute to urban ecosystem restoration and biodiversity enhancement. For example, in a catchment-level trial in Melbourne, the implementation of 289 stormwater retention systems resulted in a significant increase in the diversity of vegetation and aquatic insects within the catchment, as well as significant improvements in ecological connectivity [22].

Meanwhile, several "sponge city" projects in China, where stormwater wetlands provide suitable habitats for birds and amphibians, have increased bird abundance by 35% [16]. Vegetation filtration belt further promoted the stability of urban ecosystem by increasing the coverage of local plants [21].

3.3. Mitigation of urban heat island effect

Stormwater management facilities have been remarkably successful in mitigating the urban heat island effect by increasing green space cover and increasing evaporation. Studies have shown that a rain garden project in Xiamen increased evaporation by 40% in summer experiments compared to traditional hardened surfaces, significantly improving the local summer microclimate [15, 23]. In addition, the green roof was able to reduce the surface temperature of the building by about 3 ° C during the summer day and provide a local cooling effect of about 1.5 ° C at night, based on measurements under high summer temperatures and rainfall conditions [15].

3.4. Groundwater recharge and water cycle reconstruction

Stormwater management facilities have important ecological significance for groundwater recharge and water cycle restoration. Infiltration paving and rain gardens alleviate the problem of over-exploitation of groundwater by facilitating the infiltration of rainwater. In the "sponge city" pilot in Suzhou, studies have shown that these measures replenish 18% of total rainfall to groundwater each year, significantly improving the urban water resource situation [16]. However, the transformation of urban soil permeability is still a technical difficulty, especially in high-density hardened areas, and it is necessary to improve the permeability through soil improvement and innovative application of recycled materials [14].

4. Existing challenges and prospects

4.1. Technical and economic constraints

The implementation of sustainable stormwater management methods is often constrained by both technical complexity and economic cost. For example, green infrastructure is expensive to build and maintain, and according to research, China's "sponge city" pilot projects need to invest about 4 million to 6 million yuan per year in infrastructure development [15]. In addition, the diversity of different urban ecosystems also increases the difficulty of technical adaptation, such as the demand for rainwater permeation pavement in high-density hardened areas is much higher than that in low-density areas [18].

4.2. Social and policy barriers

Social and policy factors also hinder the promotion of stormwater management. The general lack of public awareness of the ecological benefits of stormwater management resulted in a low support rate at the community level [19]. In addition, the lack of policy support and legal frameworks significantly limits the rollout of green infrastructure. For example, in some developing countries, the lack of financial capacity of local governments has made it difficult to form effective public-private partnership models [24].

4.3. Necessity of academic and technical collaboration

Stormwater management requires a multidisciplinary collaboration of engineering, ecology and social sciences. At present, most cities lack a unified technical standard and implementation framework for stormwater management, which limits the promotion and optimization of management methods [16]. Strengthening collaboration between academia and industry to drive innovation in sustainable stormwater management solutions through data sharing and technology development is key to addressing current challenges.

5. Conclusion

This paper systematically contrasts traditional and sustainable stormwater management approaches and highlights their contributions to improving urban ecosystems and enhancing climate resilience. Traditional approaches, such as centralized drainage systems and stormwater storage technologies, have played a key role in alleviating urban waterlogging and addressing water scarcity, but have limitations in reducing non-point source pollution and promoting ecological restoration. In contrast, sustainable approaches such as low-impact development, sponge cities, and smart stormwater management systems offer a more comprehensive solution. These methods significantly improve ecological functions by improving water quality, restoring habitat, mitigating the heat island effect, and facilitating groundwater recharge.

By combining nature-based solutions with advanced technologies, the sustainable approach demonstrates excellent adaptability to diverse urban conditions and makes an important contribution to long-term ecological restoration and response to climate change.

Future research should focus on developing more adaptable interdisciplinary approaches to stormwater management. This includes strengthening the collaboration of engineering, ecology and social sciences to design solutions tailored to different urban conditions. Furthermore, the long-term ecological effects of stormwater management measures need to be continuously monitored to optimize their implementation and sustainability. This will provide critical support for further improving the effectiveness, scalability and resilience of these approaches to climate change.

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